Liquid Lithium Divertor Characteristics and Plasma-Material Interactions in NSTX High-Performance Plasmas

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MA Jaworski, T. Abrams, J.P. Allain, M.G. Bell, R.E. Bell, A. Diallo, T.K. Gray, S.P. Gerhardt, R. Kaita, J. Kallman, H.W. Kugel, B.P. LeBlanc, R. Maingi, A.G. McLean, J. Menard, R. Nygren, M. Ono, S.F. Paul, M. Podesta, A.L. Roquemore, S.A. Sabbagh, F. Scotti, C.H. Skinner, V.A. Soukhanovskii, D.P. Stotler, and the NSTX Team

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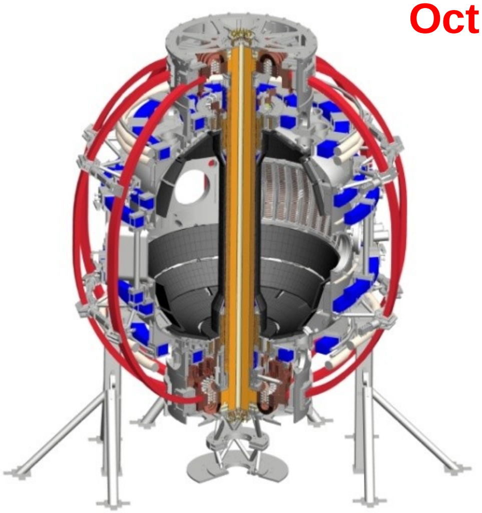

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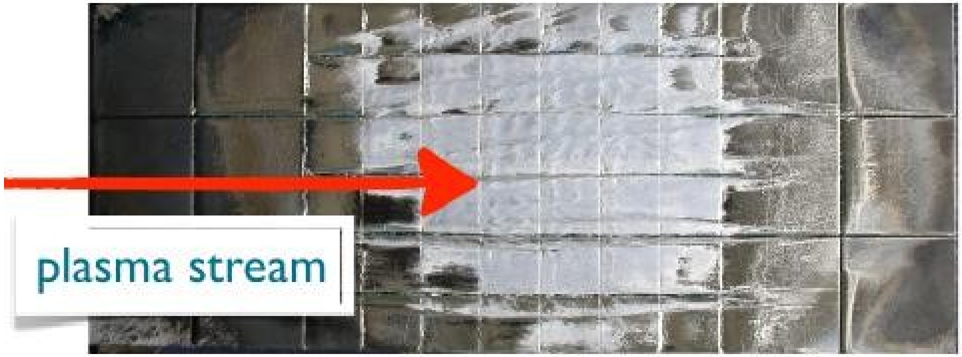
Why liquids? Because solids may not extrapolate

- Two major failure modes for solids that are known:
    - Melting (transient heat loads)
    - Net-reshaping (erosion, migration, redeposition)
- Some speculative failure modes:
    - Neutron-PMI synergistic effects (aside from bulk material changes)
    - Steady-state, self-regulating walls?

B. Lipschultz, et al., “Tungsten melt effects on C-MOD operation & material characteristics”, 20-PSI, Aachen, Germany, May, 2012.



Coenen, et al., “Evolution of surface melt damage, its influence on plasma performance and prospects of recoverhy”, 20-PSI, Aachen, Germany, May, 2012.
Klimov, et al., JNM **390-391** (2009) 721.

Wall erosion/redeposition not mitigated by divertor configuration

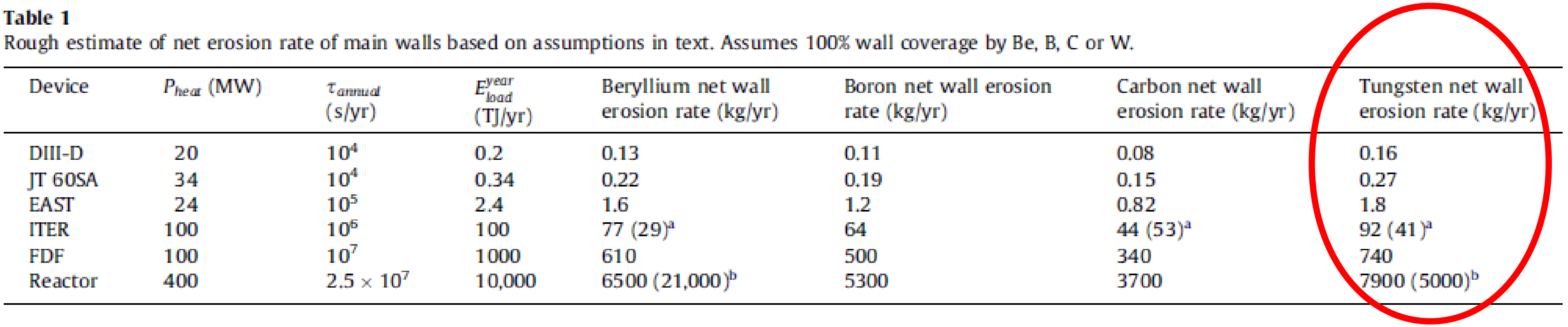


Table 1

Rough estimate of net erosion rate of main walls based on assumptions in text. Assumes 100% wall coverage by Be, B, C or W.

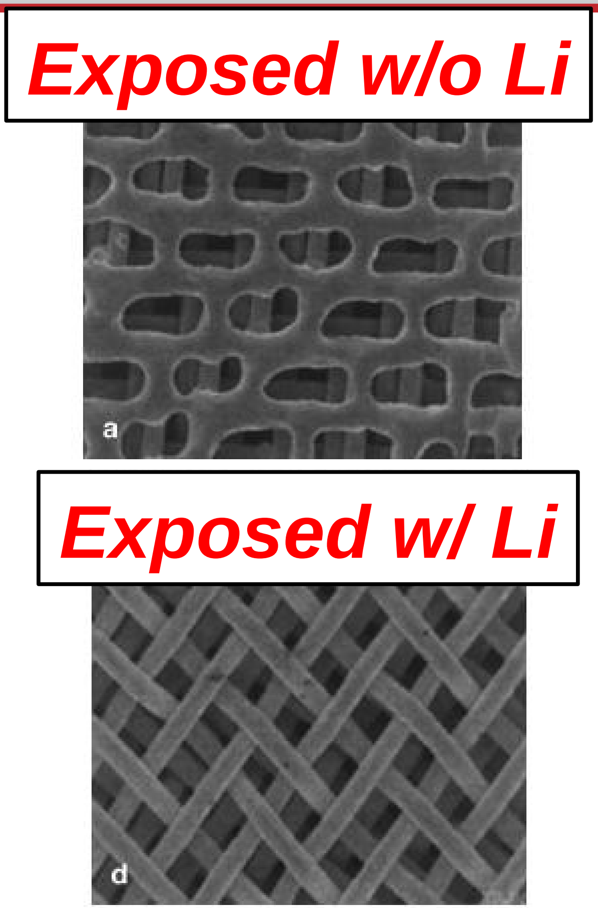
Device	P_{heat} (MW)	τ_{annual} (s/yr)	E_{load}^{year} (TJ/yr)	Beryllium net wall erosion rate (kg/yr)	Boron net wall erosion rate (kg/yr)	Carbon net wall erosion rate (kg/yr)	Tungsten net wall erosion rate (kg/yr)
DIII-D	20	10^4	0.2	0.13	0.11	0.08	0.16
JT 60SA	34	10^4	0.34	0.22	0.19	0.15	0.27
EAST	24	10^5	2.4	1.6	1.2	0.82	1.8
ITER	100	10^6	100	77 (29)[a]	64	44 (53)[a]	92 (41)[a]
FDF	100	10^7	1000	610	500	340	740
Reactor	400	2.5×10^7	10,000	6500 (21,000)[b]	5300	3700	7900 (5000)[b]

P.C. Stangeby, et al., JNM 415 (2011) S278.

- Charge-exchange processes create steady wall-flux
- Low density plasma at first wall reduces local redeposition
- **1000s of kgs** of eroded material migrating around tokamak vessel
- Likely to redeposit in locations where cooler plasmas exist or behind baffled areas of machine
- Do PFCs remain functional with large amounts of redeposited material?
  - Need very high duty-factor to even study the problem!

Liquids already shown to outperform solids in some areas

- Red Star Capillary-Porous-System (CPS) long-since shown to resist melting damage – protect the substrate
  - CPS surface consists of metal mesh wicking structure (Mo mesh)
  - Capillary forces maintain liquid lithium on plasma-facing surface
- Also shown to absorb, in steady-state, 1-25 MW/m^2
  - Electron beam heating of the surface
  - Tests lasted between 30s-10min
- In principle, all PFCs in fully-flowing system will return to an equilibrium position (i.e. self-healing)

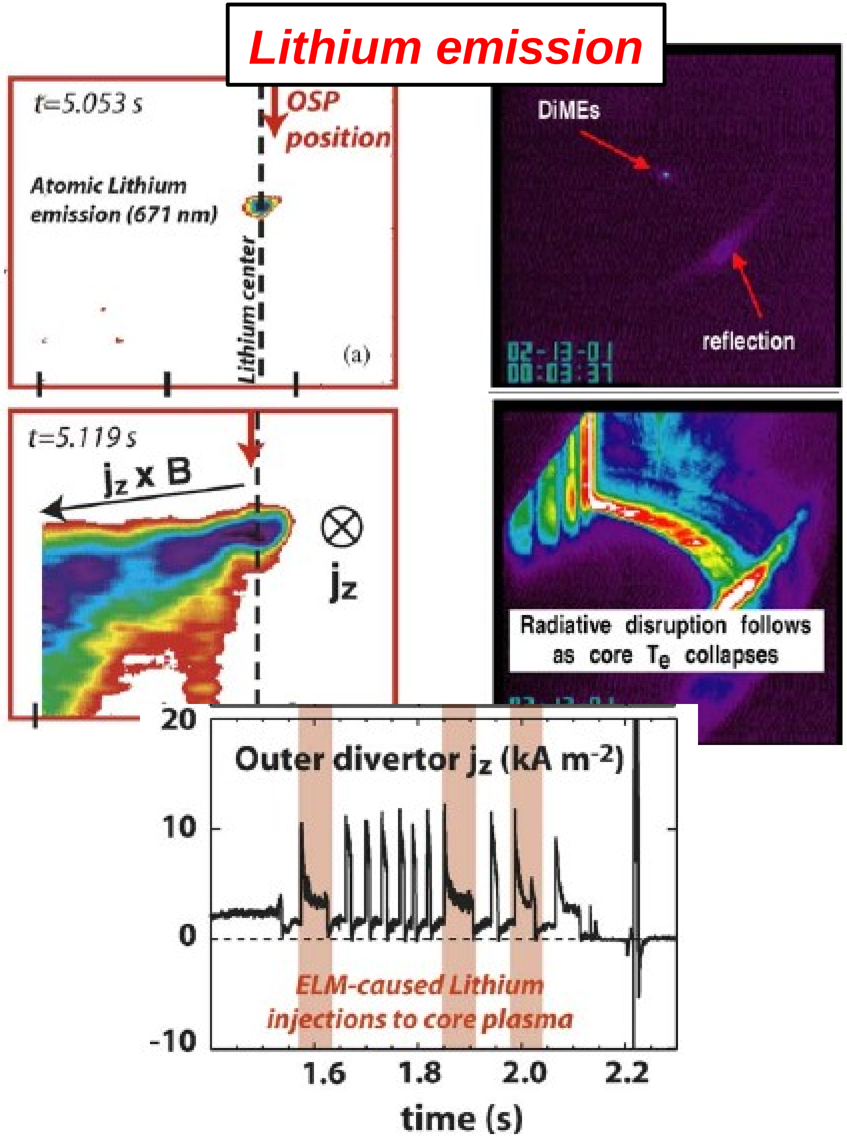


CPS Mo meshes after plasma exposure. Top did not have lithium fill during exposure. 15-100μm pores

Evtikhin, et al., J. Nucl. Mater. **271-272** (1999) 396.

Stability of the free-surface LM is critical

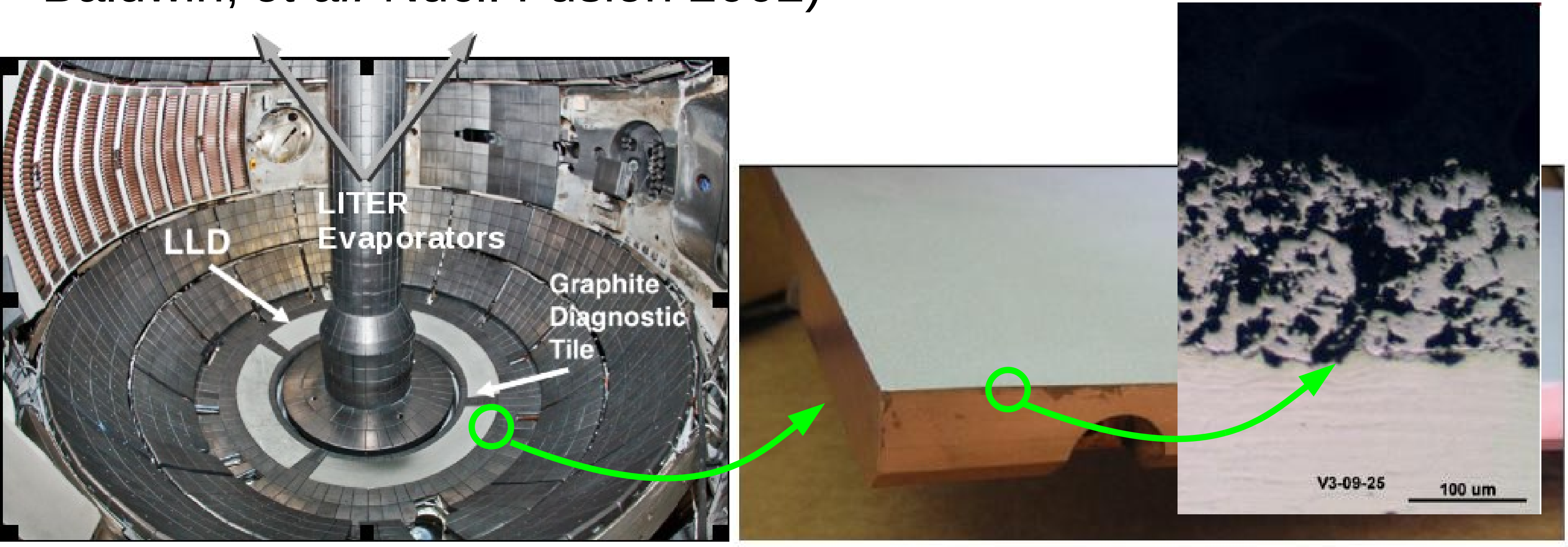
- •DIII-D Li-DIMES experiments ended in plasma disruption
  - Introduced small sample of Li into divertor of DIII-D
  - Current perturbations measured up to 10 kA/m^2
  - Li plume observed when lithium ejected from sample holder
  - Disruption shortly follows lithium ejection
- •If relying on LM to protect substrate, need robust solution
  - – Protect against steady-state and transient events
  - – **We show NSTX LLD exhibits stability in the divertor**



Whyte, et al., Fusion Eng. Des. **72** (2004) 133.

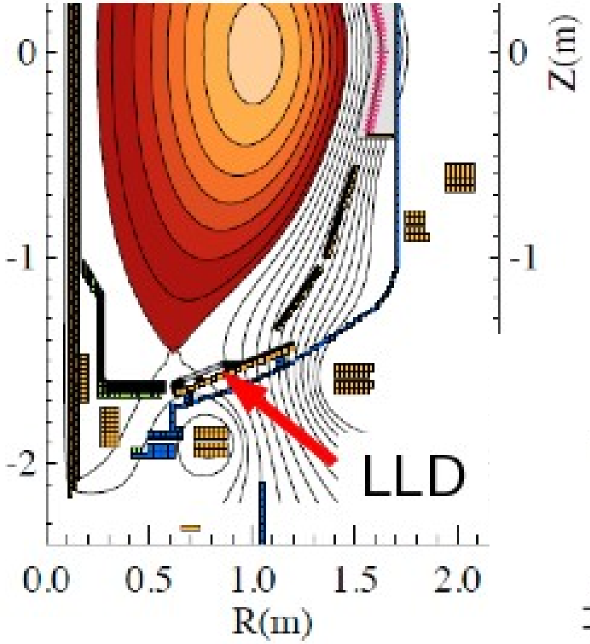
NSTX experience with the Liquid Lithium Divertor

- Liquid lithium divertor installed for FY2010 run campaign
- 2.2cm copper substrate, 250μm SS 316, ~150μm flame-sprayed molybdenum, loaded via LITER evaporators
- 37g estimated capacity, 60g loaded by end of run campaign
- Motivated to explore liquid lithium pumping of deuterium (c.f. Baldwin, *et al.* Nucl. Fusion 2002)



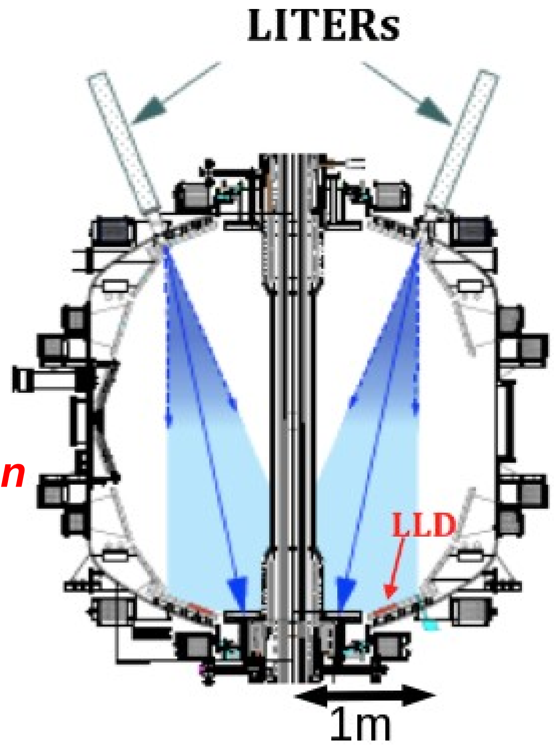
Overview of experiments

- Experiments diverting onto the LLD occurred throughout run campaign
- Either diverted onto LLD or just inboard on ATJ graphite
- LITER only available filling method for the LLD
  - 7% filling efficiency estimated
  - Always coating entire lower divertor in addition to LLD
- Database of shots taken throughout run year



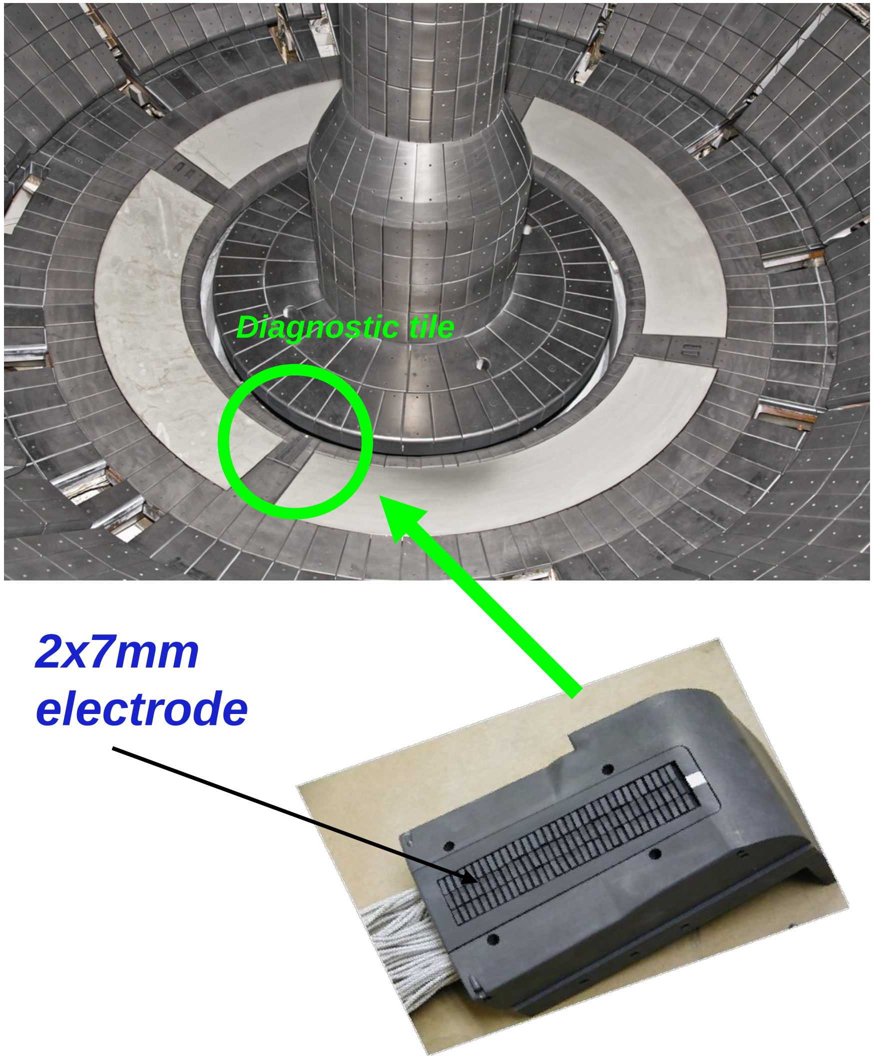
No boronization campaign prior to lithium introduction

Database already starts with 60g inventory in vessel



High-density Langmuir probe array installed for divertor plasma characterization

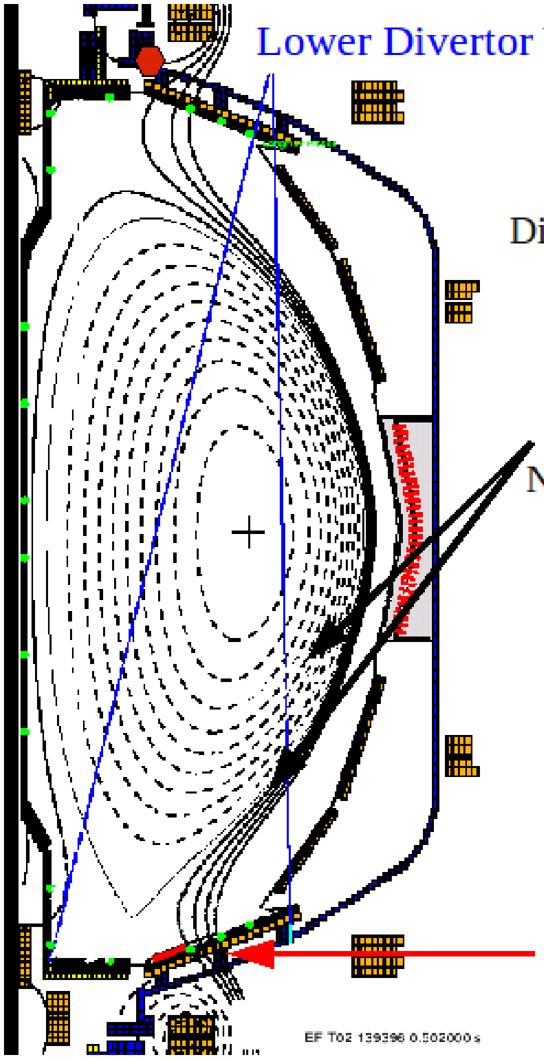
- Liquid Lithium Divertor (LLD) installed to study lithium plasma-material interactions
- Probe array characterizes local plasma properties in a range of experiments
- Provides high spatial density of measurements
- Oblique incidence yields smaller effective probe size



J Kallman, RSI 2010
MA Jaworski, RSI 2010

Empirical plasma reconstruction provides framework for checking consistency between diagnostics

- Utilizes measured data points as starting point in constraining plasma models to fill the gaps between diagnostics
- Solution improves as more and more data constrains background
- OEDGE code suite used here: Onion-Skin Method (OSM2)+EIRENE+DIVIMP
    - OSM2 solves plasma fluid equations
    - EIRENE performs Monte Carlo neutral hydrogen transport, iteratively coupled to OSM2
    - DIVIMP performs Monte Carlo impurity transport
- Utilized here to compare probe interpretation methods against other diagnostics



Lower Divertor Views

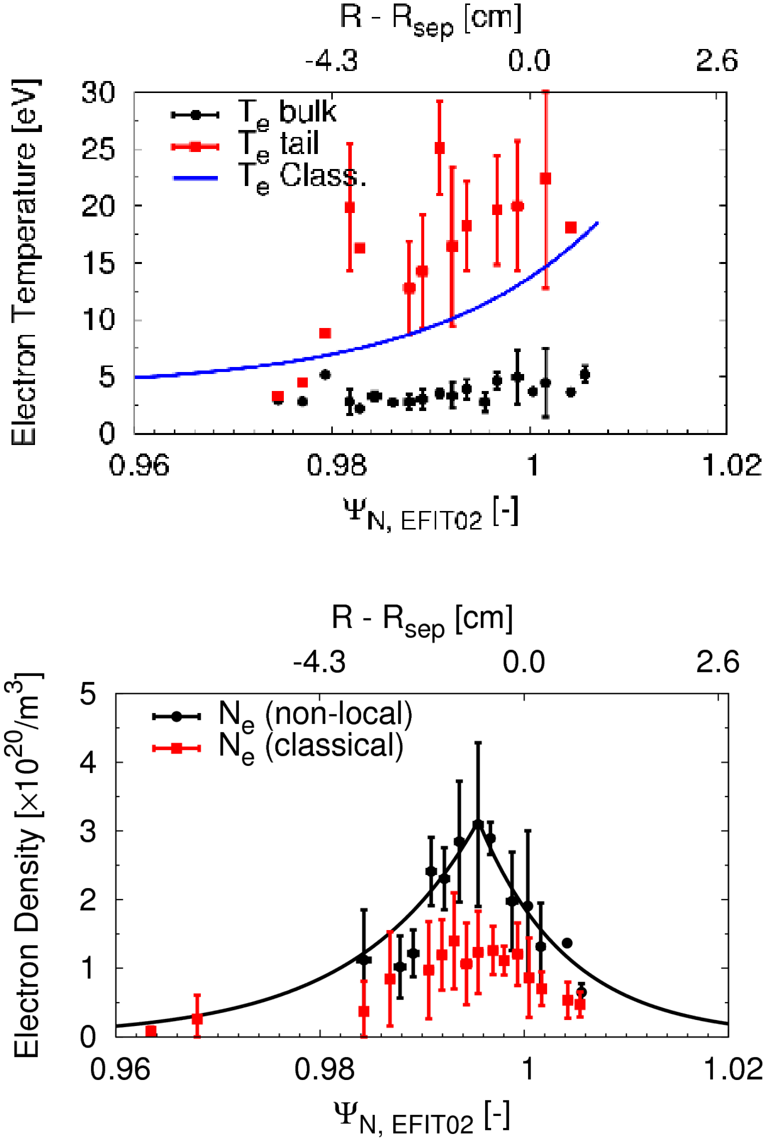
IR thermography
Line-scan camera
Fast cameras
Divertor spectroscopy

Constant magnetic flux contours
Normalized flux = ψ_N

High-Density Langmuir Probe Array

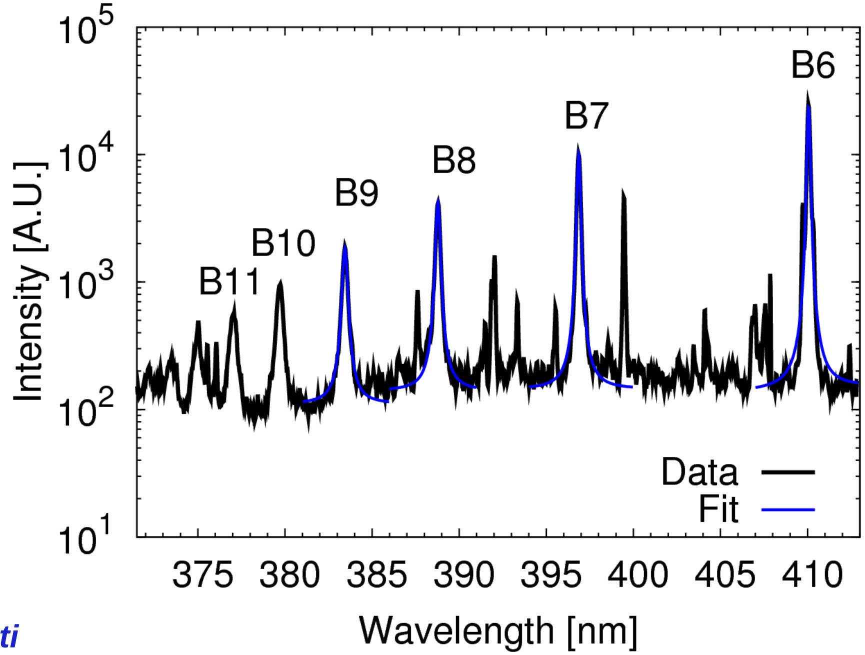
Accurate diagnosis of plasma parameters critical to assessing local PMI

- Plasma motion sweeps out profile during discharge, data aggregated and averaged
    - Nominal equilibrium separatrix location at $\psi_N = 1.0$
    - I_{sat} peak provides indicator of LP-based separatrix location
- Significant temperature variance between interpretation methods
    - 10-20eV temperatures with classical method
    - 2-5eV temperatures with non-local interpretation
- Lower temperatures result in higher densities with kinetic interpretation



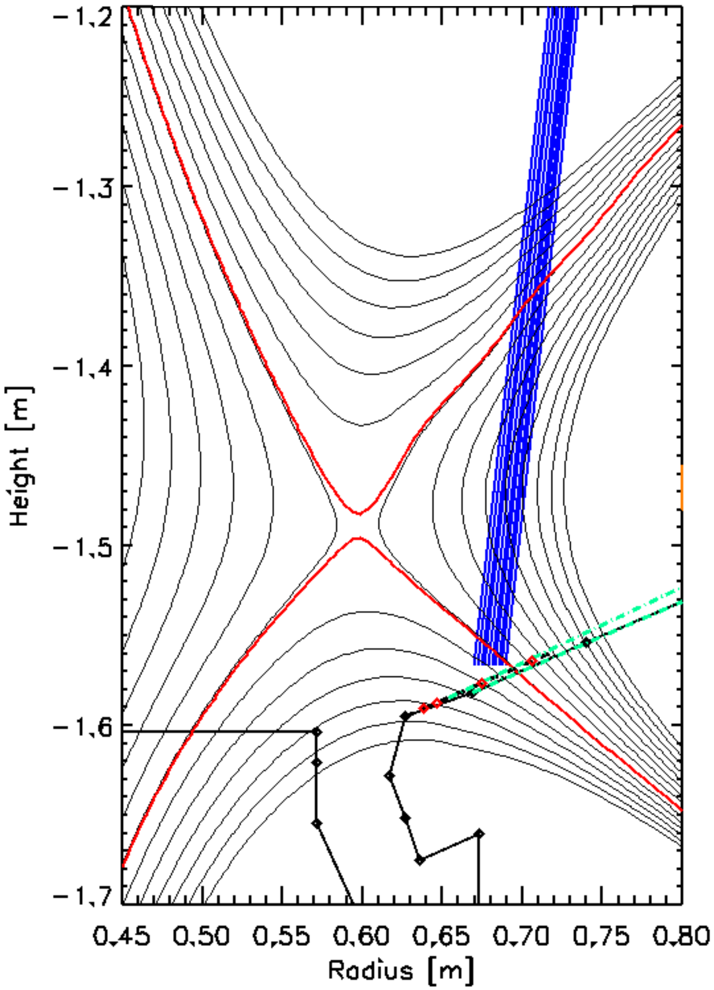
Density measurement from spectroscopy first confirmation of kinetic probe interpretation

- •Divertor spectrometer viewing strike-point region during discharge
- •Deuterium Balmer lines shown in spectra
- •Pressure broadening analysis indicates dneisty of 3.6e20 m^{-3}
  - Existence of high-n Balmer lines indicates low temperature



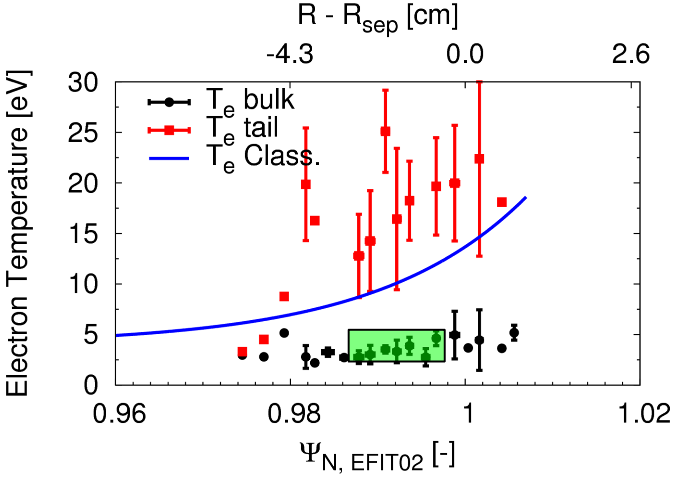
F. Scotti

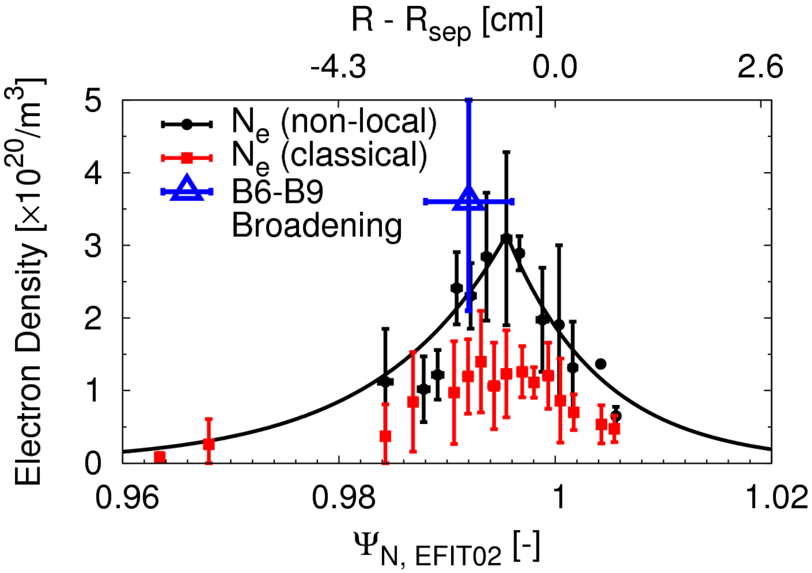
Divertor spectrometer view

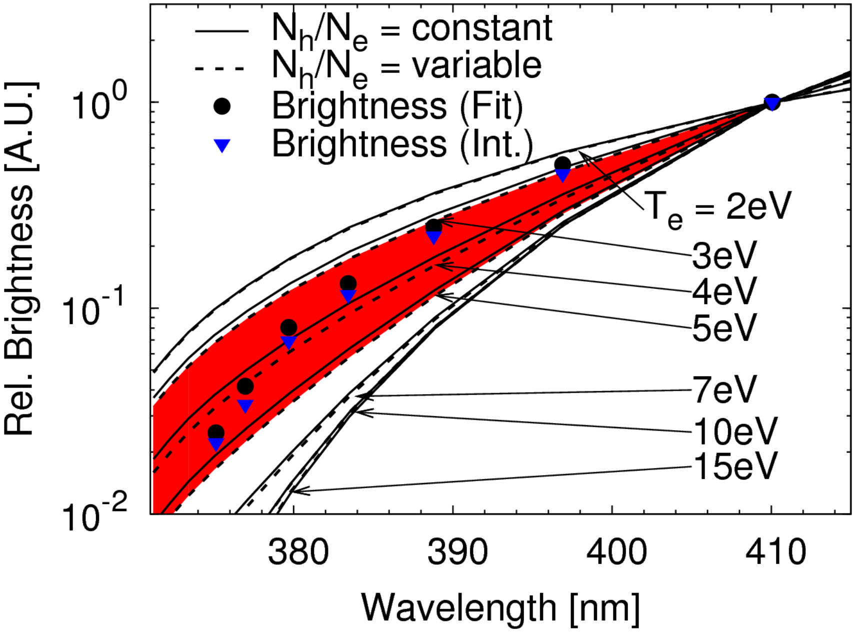


Broadening measurement and modeling of hydrogen spectrum consistent with kinetic interpretation

- Pressure broadening yields density
- OEDGE plasma+neutral solution provides local parameters
- Collisional-radiative model by D. Stotler calculates excited state populations
- Brightness ratios normalized to B6 consistent with 3-5eV







Jaworski, et al., 20th PSI, Aachen, Germany, June 2012.

Empirical reconstruction indicates classical values for the sheath heat transmission coeff. obtained with bulk T_e

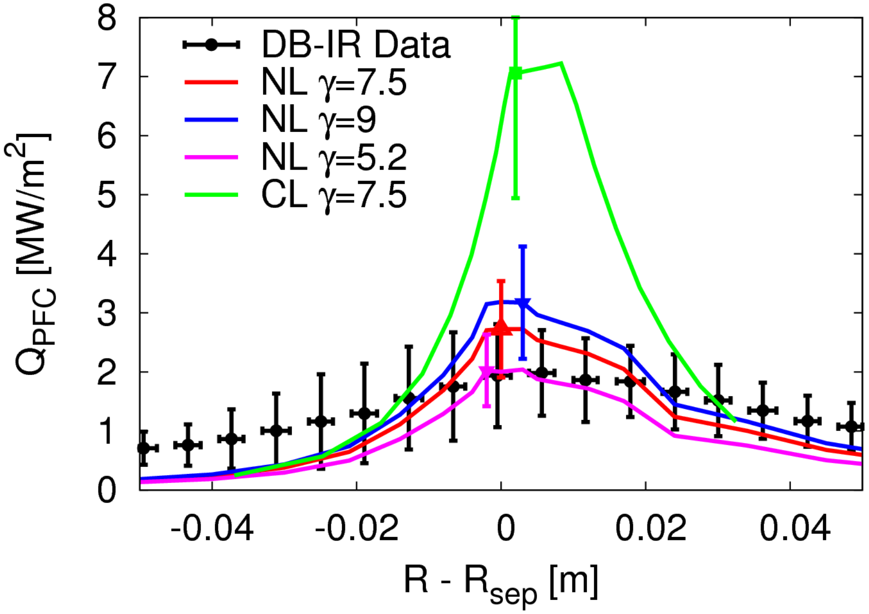
- Sheath heat transmission coefficient, γ, determines the amount of power transferred to a material surface
  - Fluid theory provides theoretical minimum of 5.2 for D plasma[1]
  - Previous experiments often indicate lower γ (e.g. γ~2)[2,3]
- Calculated γ depends sensitively on T_e
- OEDGE (OSM2 + EIRENE) background plasma created from LP data
  - Total heat flux to PFCs calculated using plasma, neutrals and rad.
  - Bi-modal distribution γ~9 estimated from multi-component plasma
- Dual-band IR heat flux[4] indicates non-local interpretation in better agreement

$$q_{classical} = \gamma \Gamma k T_e = \gamma \frac{j_{sat}^{+}}{e}(kT_e)$$

$$\gamma(V) = -\frac{eV}{kT_e} + 2.5\frac{T_i}{T_e} + \cdots$$

$$2\left[\left(1+\frac{T_i}{T_e}\right)\left(\frac{2\pi m_e}{m_i}\right)\right]^{-1/2} e^{\frac{eV}{kT_e}}$$

$$\gamma_{min,D} \approx 5.2 \qquad \gamma = \frac{q_{tot}}{\Gamma k T_e}$$



Jaworski, et al., 51st APS-DPP Invited Presentation.

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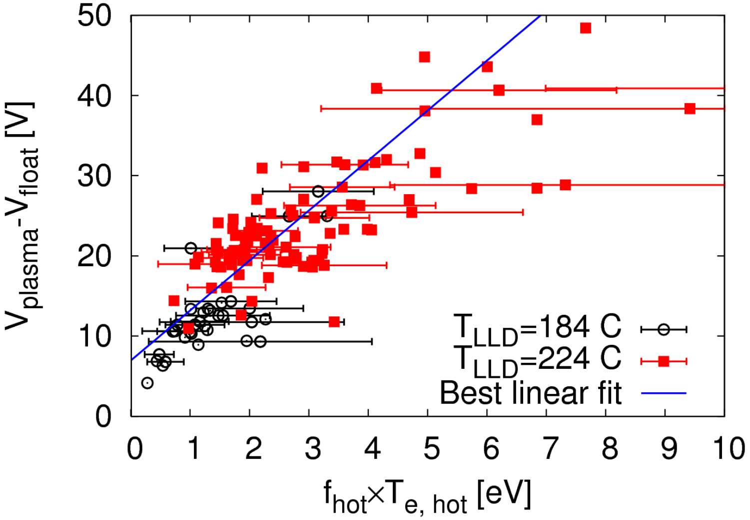
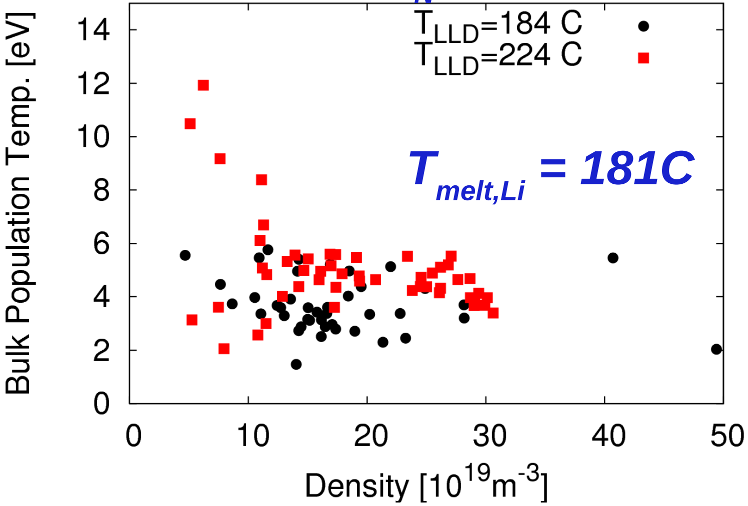
[1] *PC Stangeby, 2000, ibid.*; [2] *D Buchenauer, JNM, 1992;*
[3] *J Kallman, PP9.00043*; [4] *AG McLean, PP9.00069*

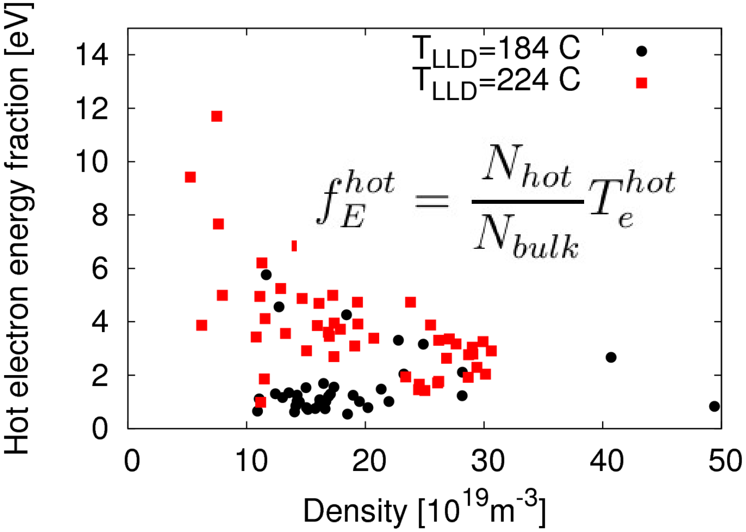
Distribution function analysis indicates some local changes in plasma conditions on plasma-heated LLD

- Discharge sequence repeatedly heated and plasma-conditioned the LLD surface
- Local plasma temperatures elevated with hotter LLD surface temperature ($T_{LLD} > T_{melt,Li}$)
- Increase in plasma temperatures correlated with increase in V_p-V_f potential difference[1]
- Understanding the changes during lithium experiments requires us to first find some model for the non-Maxwellian distributions...



Comparisons made on identical ψ_N locations

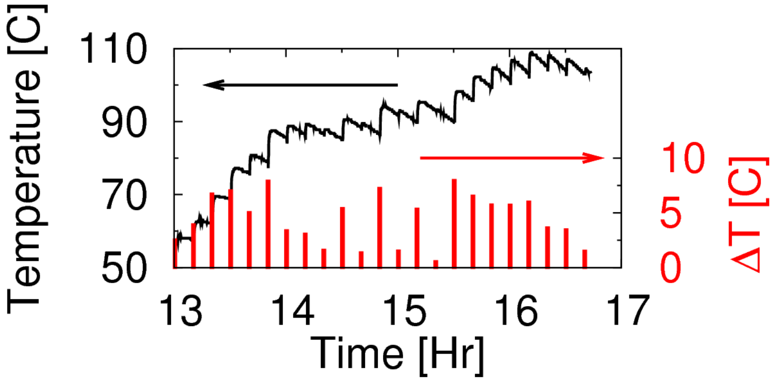


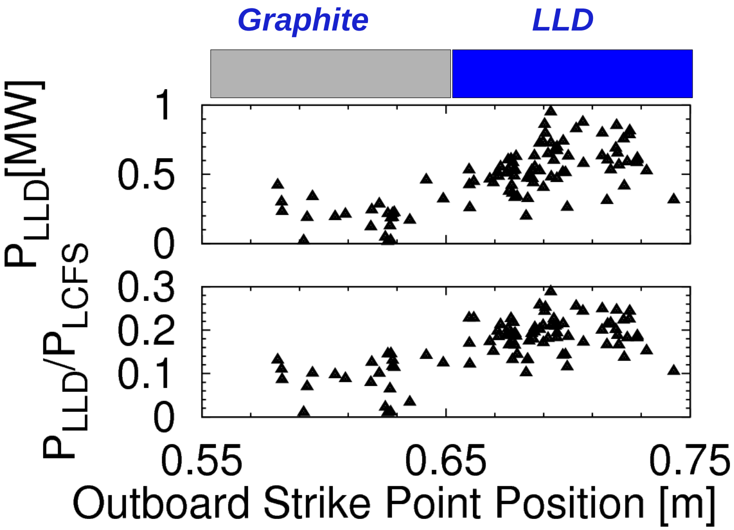


[1] *Jaworski et al., Fusion Eng. Des. 87 (2012) 1711.*

Significant power onto LLD measured

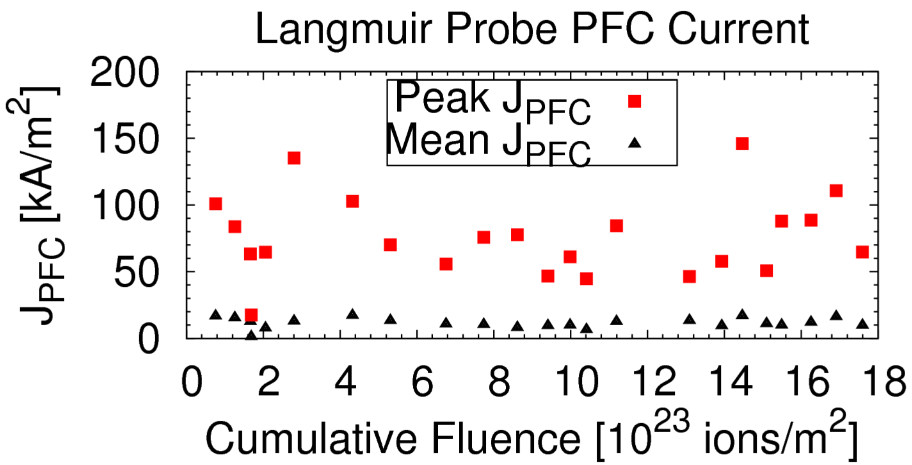
- Embedded thermocouples provide measure of temperature changes from before and after discharge
- Each plate is 43kg of copper
  - $\Delta E = mc_p \Delta T$ per plate
  - $P_{LLD} \sim 4\Delta E / \tau_{pulse}$
  - $P_{LCFS} = P_{NBI} + P_{OHM} - P_{RAD} - dW/dt$
- LLD absorbing about 25% of exhaust power
  - ~1MW in some cases
- No molybdenum observed in the plasma after melted (Soukhanovskii, **RSI**, 2010)

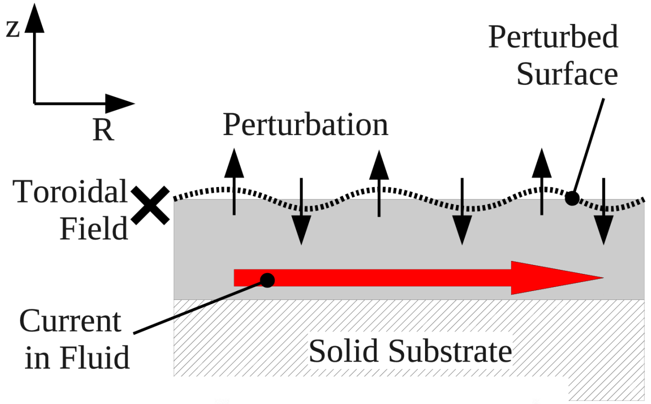




Jaworski, et al., IAEA FEC 2012

No macroscopic ejection of lithium observed; Demonstration of Stable Operation of LM PFC in Divertor Configuration





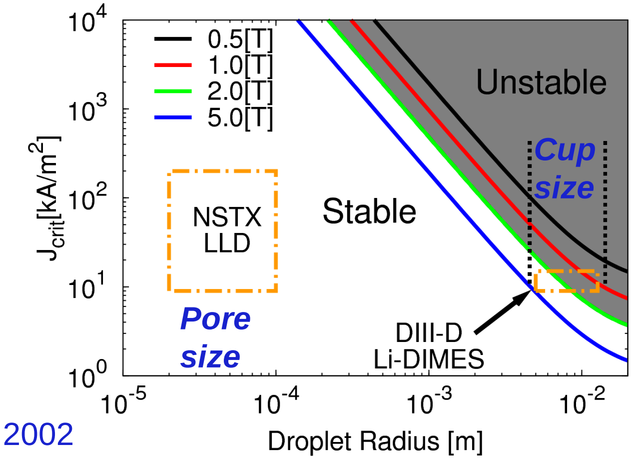
$$\exp(ik_x x + ik_y y + nt)$$

$$n^2 = k(jB/\rho - g)\left[1 - \frac{k^2\Sigma}{(jB/\rho - g)\rho} - \frac{B^2 k_x^2}{2\pi\mu_0(jB/\rho - g)\rho k}\right]$$

$$k_{Cr} = \sqrt{\frac{jB - \rho g}{\Sigma}}$$

For the fastest growing modes

- Large transient currents measured with Langmuir probes
- Magnetized Raleigh-Taylor analysis provides stability curves
- Indicates strong stabilization expected with small feature sizes
- CPS tests also reduced droplet ejection with smaller pore sizes*



Jaworski **JNM** 2011, Jaworski IAEA FEC 2012, Whyte **FED** 2004, *Evtikhin **JNM** 2002

Surface contamination indicates this was not a “fair” test of a liquid lithium PFC

- Divertor filterscopes provide indicator of impurities
  - Relative fraction of impurity should be reflected in sputter yield
  - Particle flux proportional to power
- Normalization against flux indicates no difference diverted onto the LLD
- Plasma cleaning in PISCES-B did show oxygen reduction*
  - 400s, T>600K
  - LLD transiently exceeded these temperatures, but not steady

What is relevant time scale?

$$\epsilon_{imp} \propto N_{imp} \propto Y_{imp} J_{sat}$$

$$Y_{imp} \propto Y^{0}_{imp} \theta_{imp}$$

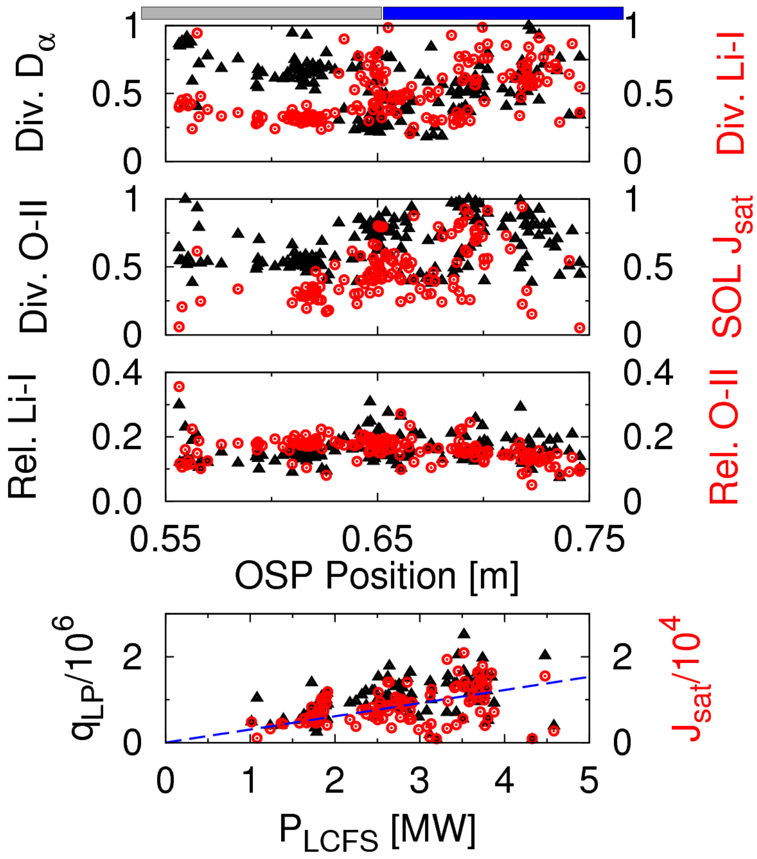
$$P \propto \gamma J_{sat} T_{e}$$

$$\theta_{imp} \propto \frac{\epsilon_{imp}}{P}$$

Emission ϵ

Coverage θ

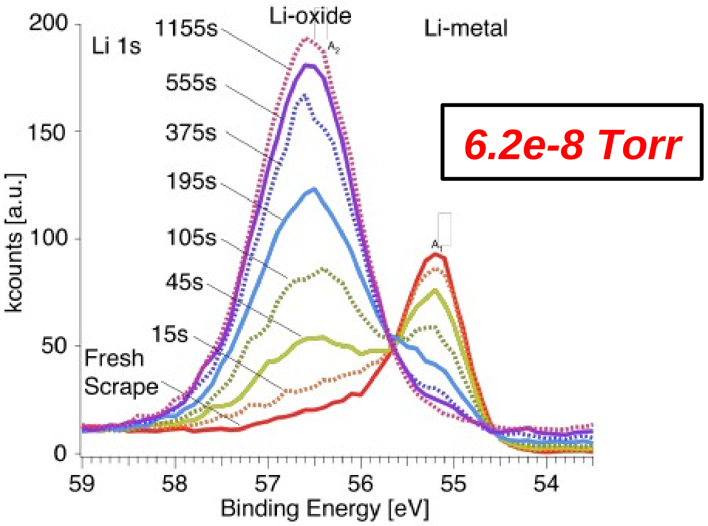
Divertor Power P



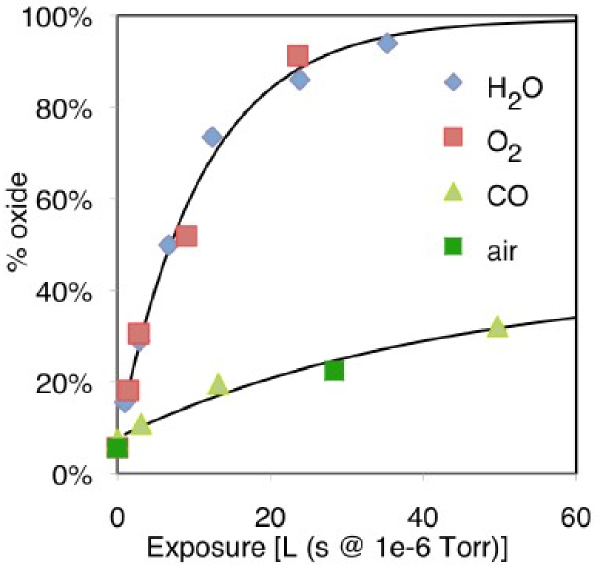
Jaworski IAEA FEC 2012, *Baldwin **NF** 2002.

Laboratory studies show rapid contamination

- New surface science laboratories at PPPL via Princeton Univ. collaboration
- High Resolution X-ray Photo-Spectroscopy (HR-XPS) measurements
  - Measure amount of oxide vs. clean lithium metal on TZM substrate
  - Expose to different gases
- Significant oxidation in 20s @ 1e-6 Torr partial pressure O_2, H_2O
  - NSTX intershot pressure ~ 1e-7 Torr
  - $\tau_{intershot} \sim \tau_{oxidize}$ indicates oxidation likely



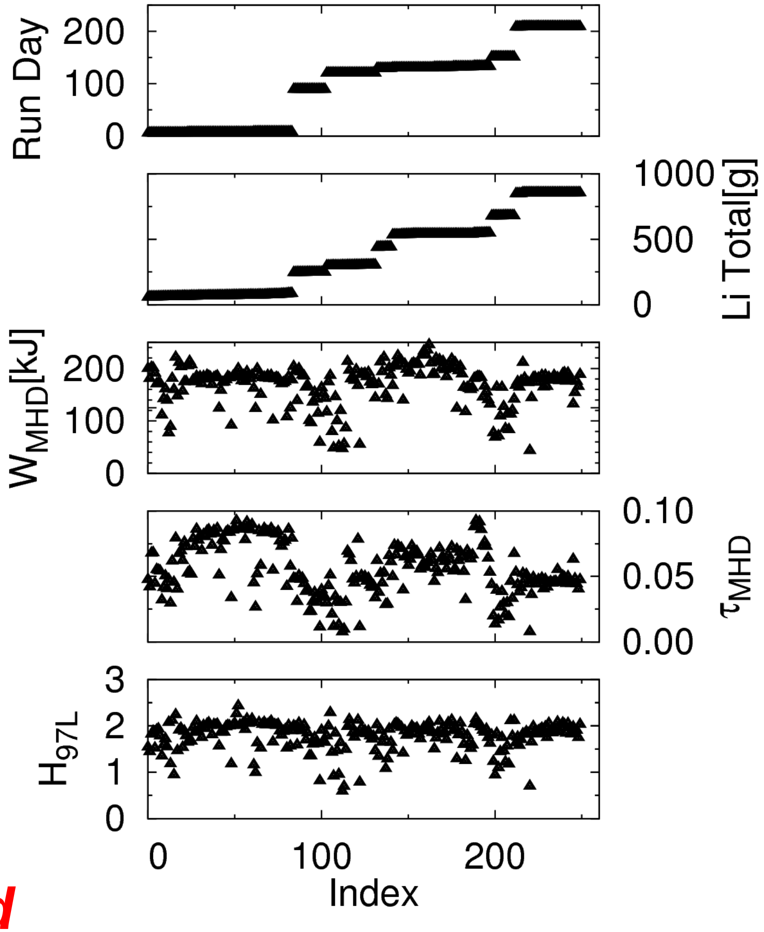
6.2e-8 Torr



Skinner, et al., 20th PSI, *submitted to JNM.*

Performance should be independent of lithium quantity *if* surface contamination is key variable

- FY2010 LLD experimental set
  - Experiments span 60g to nearly 1kg of deposited lithium
  - Includes 75hr deposition at mid-year
  - Calculate ITER 97L H-factor *average* from 400-600ms for each discharge
- Discharges look about the same between start and end of run
  - Consistent with surface contamination hypothesis



Fully-flowing PFC can provide a means of sweeping away gettered material and creating "stationary" surface conditions.

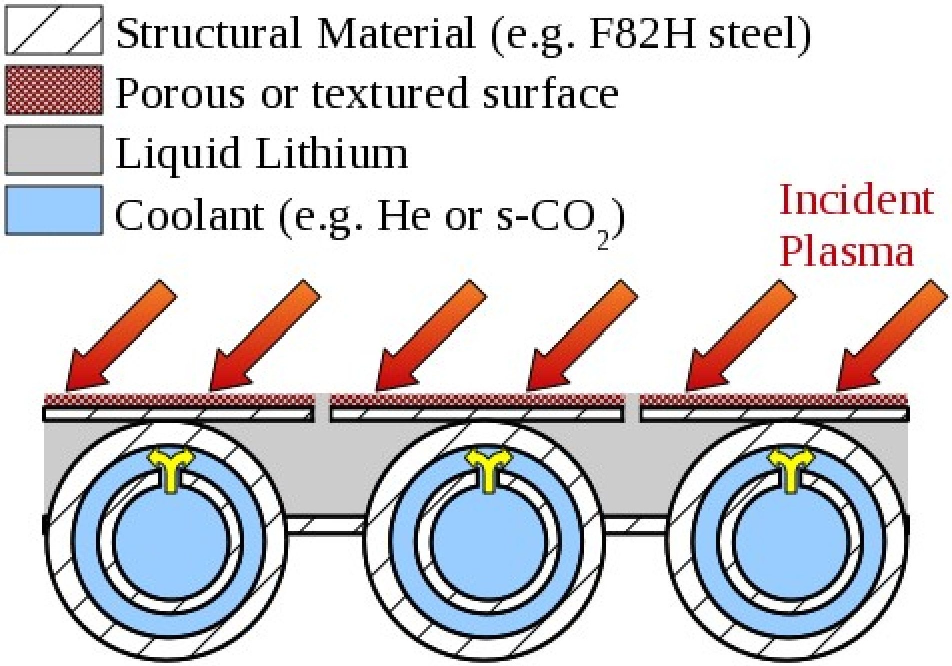
Jaworski, et al., IAEA FEC 2012

Flowing system studies are being pursued in the US

- Thermoelectric MHD systems
  - “Passive” pumping
  - Mixed convective/conductive heat removal scheme
  - U-Illinois LIMIT
- Actively-supplied, capillary-restrained systems
  - Thin layers of liquid metal
  - Conduction dominated
  - PPPL efforts
- Fundamental studies of interface dynamics, wetting, surface chemistry
  - “Liquid Metals as Plasma-Facing Materials for Fusion Energy Systems: From Atoms to Tokamaks” -H. Stone (Princeton U)
  - Newly funded work this year

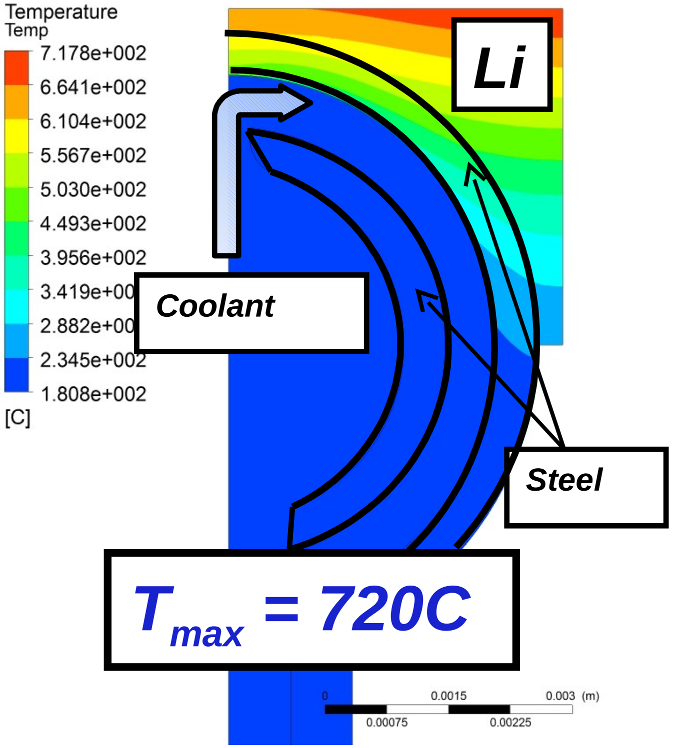
Active supply, capillary-restrained systems (PPPL)

- Hybrid approach to join flow-thru loop with active cooling
  - Leverage numerous results an experience with thin, capillary-restrained concepts
  - Maintain thin structures (as thin as possible) to maximize heat transfer to coolant
- Modular approach considered to provide optimization space
  - T-tube concept shown, other gas cooling schemes available (e.g. SOFIT, vapor-box/heat pipes)
  - Surface could be flame-sprayed or other scheme (e.g. laser textured)



Current work-in-progress: steel with low-Z lithium coating

- T-tube size reduction to reduced required wall thickness, s-CO2 coolant
- F82H steel properties with liquid lithium
  - Liquid lithium evaporative cooling included
  - 10 MW/m^2 heat flux simulated, no nuclear heat
  - No provision for plasma response
- Steel structure maintained below ~650C, close to range for ODS-steel operation*



T_{max} = 720C

Still optimizing/developing 3D solution, 720C might be too hot**

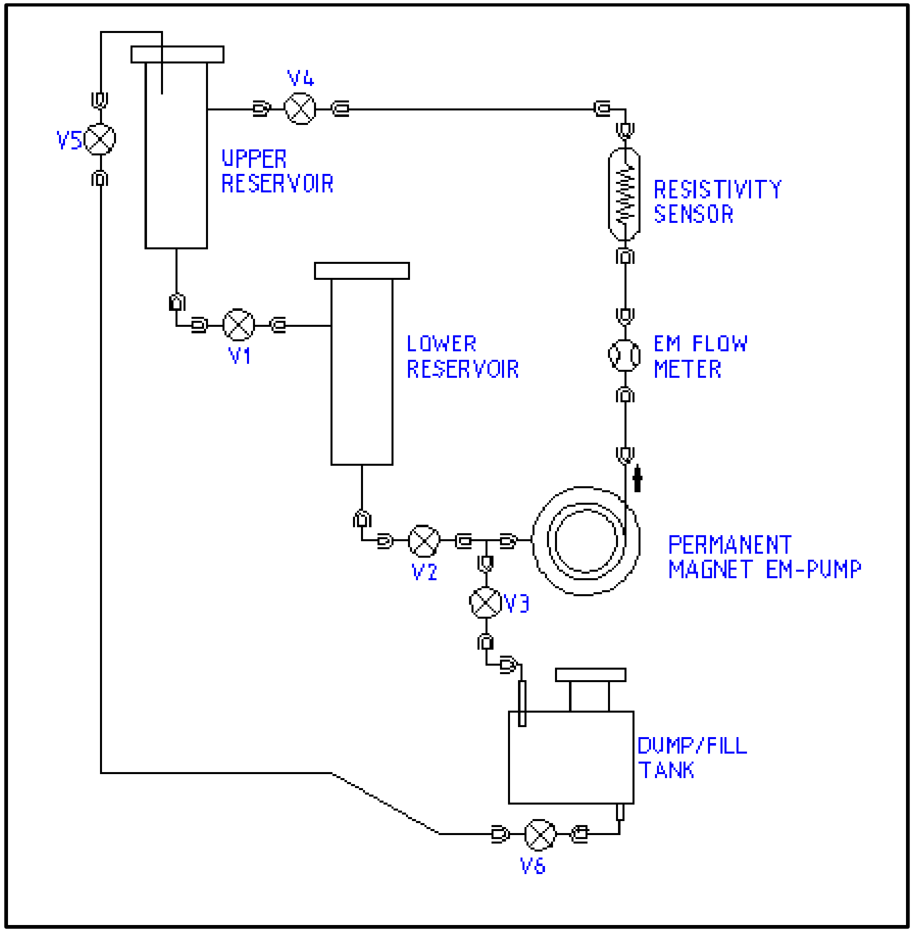
*Zinkle,, Ghoniem, Fusion Eng. Des. **51-52** (2000) 55.

Apiccella, et al., PPCF **54 (2011) 035001.

Experiment construction underway to provide testbed for PFCs and demonstration of necessary technologies

- Liquid lithium loop for experimental demonstration
  - Safe operation of loop
  - Robust operation and maintainability
  - Develop control systems, handling procedures
  - Look toward integration with tokamak systems
- PFC proof-of-principle tests
  - Couple to vacuum system
  - Demonstrate LM concepts in relevant vacuum environment

Liquid Lithium Test Stand Loop Diagram



Liquid metal research proceeding on multiple fronts

- Liquid metals offer potential solutions to the problems facing solid PFCs

- NSTX Liquid Lithium *Divertor* experience confirms many results obtained on limiter machines

- Contamination by residual gases motivates a flowing system

- Liquid metal PFC development ongoing at PPPL to develop next-step divertor solutions

Reprints